

Beyond the SM phenomena and the extended Higgs sector based on the SUSY gauge theory with confinement

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We propose a fundamental theory whose low-energy effective theory provides a phenomenological description of electroweak baryogenesis, radiative neutrino mass generation, and dark matter. The model is based on SUSY $SU(2)_H$ gauge theory with confinement, and the model contains new Z_2 discrete symmetry and Z_2 -odd right-handed neutrino superfields. The Higgs sector in the low energy effective theory of this model below confinement scale is described by fifteen mesonic superfields of fundamental $SU(2)_H$ doublets. We present a benchmark scenario of this model, where all the constraints from the current neutrino, dark matter, lepton flavour violation and LHC data are satisfied. We also discuss how to test the scenario by the future collider experiments.

I. INTRODUCTION

Though the standard model (SM) is established by the discovery of the SM-like Higgs boson, new physics beyond the SM are still required for solving several serious problems such as a mechanism to produce the baryon asymmetry of the Universe (BAU), a origin of tiny neutrino masses, and a candidate of the dark matter (DM),

It is interesting to focus on the scenarios which solves these three problems at around the TeV scale, *i.e.* the electroweak baryogenesis[1] for the mechanism for producing BAU, radiative seesaw scenarios for the origin of tiny neutrino masses, and introducing weak interacting massive particles as candidates of the DM. Many nice models in such a direction have been developed in literature. In particular, the Aoki-Kanemura-Seto (AKS) model[4] is an attractive example which includes all the three mechanisms.

However, in the AKS model, it is known that a Landau pole appears at the scale much below the Planck scale. It means that there should be a more fundamental theory above a cutoff scale. In the following, we review a candidate of such a fundamental theory proposed in Refs. [2, 3], which is based on a supersymmetric (SUSY) gauge theory with confinement.

II. THE MODEL

It is known that confinement occurs in the $SU(N_c)$ SUSY gauge theory with N_f flavours when $N_f = N_c + 1$ is satisfied[5]. The simplest case is $N_c = 2$ and $N_f = 3$. We utilize this simplest setup and propose a SUSY $SU(2)_H$ gauge theory¹ In order to forbid tree level contributions to neutrino masses, an unbroken Z_2 symmetry is introduced to the model. We also introduce a right-handed neutrino (RHN) superfield which has odd number under the Z_2 symmetry. The assignment of the SM charge and the Z_2 -parity on the $SU(2)_H$ doublets and the RHN is shown in Table I-(I).

In this framework, the $SU(2)_H$ gauge coupling becomes strong at a certain scale Λ_H , and the low energy effective theory below Λ_H is described in terms of the fifteen mesonic fields listed in the Table I-(II), where the mesonic superfields are canonically normalized as $H_{ij} \simeq \frac{1}{4\pi\Lambda_H} T_i T_j (i \neq j)$. The superpotential of the Higgs sector in the low energy effective theory can be written as

$$W_{\text{eff}} = \lambda N (H_u H_d + v_0^2) + \lambda N_\Phi (\Phi_u \Phi_d + v_\Phi^2) + \lambda N_\Omega (\Omega_+ \Omega_- - \zeta \eta + v_\Omega^2) + \lambda \{ \zeta H_d \Phi_u + \eta H_u \Phi_d - \Omega_+ H_d \Phi_d - \Omega_- H_u \Phi_u - N N_\Phi N_\Omega \} . \quad (1)$$

It is naively expected that $\lambda \simeq 4\pi$ at the confinement scale Λ_H . The relevant part of the soft SUSY breaking

¹ It's the same setup as the minimal SUSY fat Higgs model[6]. In the minimal SUSY fat Higgs model, only H_u , H_d , and N are made light by introducing additional fields. On the other hand, all the mesonic fields listed in Table I-(II) play an important role in our model.

TABLE I: (I) The charge assignment under the SM gauge group $(SU(3)_c \times SU(2)_L \times U(1)_Y)$ and the Z_2 parity on the $SU(2)_H$ doublets T_i and the RHN N_R^c . (II) The field content of the extended Higgs sector or the low energy effective theory of the SUSY $SU(2)_H$ model.

(I)						(II)				
Superfield	$SU(2)_H$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Z_2	Superfield	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Z_2
$\begin{pmatrix} T_1 \\ T_2 \end{pmatrix}$	2	1	2	0	+1	$H_d \equiv \begin{pmatrix} H_{14} \\ H_{24} \end{pmatrix}$	1	2	-1/2	+1
T_3	2	1	1	+1/2	+1	$H_u \equiv \begin{pmatrix} H_{13} \\ H_{23} \end{pmatrix}$	1	2	+1/2	+1
T_4	2	1	1	-1/2	+1	$\Phi_d \equiv \begin{pmatrix} H_{15} \\ H_{25} \end{pmatrix}$	1	2	-1/2	-1
T_5	2	1	1	+1/2	-1	$\Phi_u \equiv \begin{pmatrix} H_{16} \\ H_{26} \end{pmatrix}$	1	2	+1/2	-1
T_6	2	1	1	-1/2	-1	$\Omega_- \equiv H_{46}$	1	1	-1	-1
N_R^c	1	1	1	0	-1	$\Omega_+ \equiv H_{35}$	1	1	+1	-1
						$N \equiv H_{56}, N_\Phi \equiv H_{34}, N_\Omega \equiv H_{12}$	1	1	0	+1
						$\zeta \equiv H_{36}, \eta \equiv H_{45}$	1	1	0	-1

Lagrangian is given by

$$\begin{aligned}
\mathcal{L}_H = & -m_{H_u}^2 H_u^\dagger H_u - m_{H_d}^2 H_d^\dagger H_d - m_{\Phi_u}^2 \Phi_u^\dagger \Phi_u - m_{\Phi_d}^2 \Phi_d^\dagger \Phi_d - m_N^2 N^* N - m_{N_\Phi}^2 N_\Phi^* N_\Phi - m_{N_\Omega}^2 N_\Omega^* N_\Omega \\
& - m_{\Omega_+}^2 \Omega_+^* \Omega_+ - m_{\Omega_-}^2 \Omega_-^* \Omega_- - m_\zeta^2 \zeta^* \zeta - m_\eta^2 \eta^* \eta - \left\{ m_{\zeta\eta}^2 \eta^* \zeta + \frac{B_\zeta^2}{2} \zeta^2 + \frac{B_\eta^2}{2} \eta^2 + \text{h.c.} \right\} \\
& - \{ C \lambda v_0^2 N + C_\Phi \lambda v_\Phi^2 N_\Phi + C_\Omega \lambda v_\Omega^2 N_\Omega + \text{h.c.} \} - \{ B \mu H_u H_d + B_\Phi \mu_\Phi \Phi_u \Phi_d + B_\Omega \mu_\Omega (\Omega_+ \Omega_- + \zeta \eta) + \text{h.c.} \} \\
& - \lambda \{ A_N H_u H_d N + A_{N_\Phi} \Phi_u \Phi_d N_\Phi + A_{N_\Omega} (\Omega_+ \Omega_- - \eta \zeta) N_\Omega + A_\zeta H_d \Phi_u \zeta \\
& + A_\eta H_u \Phi_d \eta + A_{\Omega_-} H_u \Phi_u \Omega_- + A_{\Omega_+} H_d \Phi_d \Omega_+ + \text{h.c.} \} .
\end{aligned} \tag{2}$$

After the Z_2 -even neutral fields N , N_Φ and N_Ω get vacuum expectation values (vev's), the mass parameters $\mu = \lambda \langle N \rangle$, $\mu_\Phi = \lambda \langle N_\Phi \rangle$ and $\mu_\Omega = \lambda \langle N_\Omega \rangle$ are induced.

The Yukawa couplings and the Majorana mass term of the RHN are given by

$$W_N = y_N^i N_R^c L_i \Phi_u + h_N^i N_R^c E_i^c \Omega_- + \frac{M_R}{2} N_R^c N_R^c + \frac{\kappa}{2} N N_R^c N_R^c . \tag{3}$$

III. BENCHMARK POINTS AND ITS PREDICTIONS

In the low energy effective theory of the model, the first order electroweak phase transition (1stOPT) can be enhanced by the loop contributions of extra Z_2 -odd scalar particles such as Φ_u and Ω_- strongly enough to satisfy the condition $\varphi_c/T_c > 1$, which is necessary for successful electroweak baryogenesis. Here, we focus only on the 1stOPT. In order to reproduce the BAU, we should also require new CP violating phases. We expect that we can introduce several new CP phases which contribute to the baryogenesis as in the case of MSSM[7].

Tiny neutrino masses are generated at loop levels as shown in Fig. 1. The one-loop diagrams are driven by the neutrino Yukawa coupling y_N and the three-loop diagrams are controlled by the coupling h_N^i . Because of this, two different mass squared differences are explained even if only one RHN is introduced.

Since both Z_2 -parity and R -parity are unbroken in our model, there can be three kinds of the DM candidates, *i.e.* the lightest particles with the parity assignments of $(-, +)$, $(+, -)$, and $(-, -)$. If one of these three particle is heavier than the sum of the masses of the others, the heaviest one decays and only the other two can be DM.

In the Table II, we list the definition of a benchmark scenario and its predictions, where the condition $\varphi_c/T_c > 1$ is satisfied, the neutrino masses and the mixing angles given by neutrino oscillation data can be

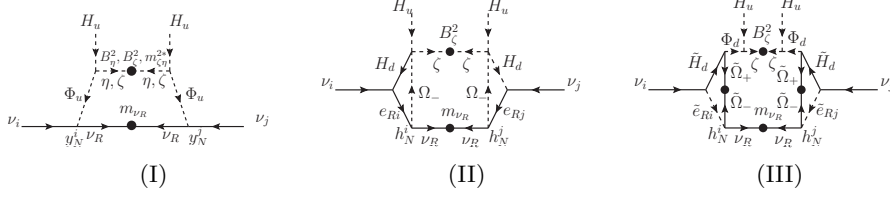


FIG. 1: (I) A one-loop diagram and (II) three-loop diagrams which contribute to the neutrino mass matrix. The figures are taken from [2]

reproduced, and the relic abundance of the DM can be explained with satisfying the constraints from the experiments such as LFV searches and the direct detection of the DM.

TABLE II: (i) The definition of our benchmark scenario, and (ii) its predictions. The tables are taken from Ref. [2].

(i) Input parameters for the benchmark scenario					
λ , $\tan \beta$, and μ -terms					
$\lambda = 1.8$	$(\Lambda_H = 5 \text{ TeV})$	$\tan \beta = 15$	$\mu = 250 \text{ GeV}$	$\mu_\Phi = 550 \text{ GeV}$	$\mu_\Omega = -550 \text{ GeV}$
Z_2 -even Higgs sector					
$m_h = 126 \text{ GeV}$	$m_{H^\pm} = 990 \text{ GeV}$	$m_N^2 = (1050 \text{ GeV})^2$	$A_N = 2900 \text{ GeV}$		
Z_2 -odd Higgs sector					
$\bar{m}_{\Phi_u}^2 = \bar{m}_{\Omega_-}^2 = (175 \text{ GeV})^2$ $\bar{m}_{\Phi_d}^2 = \bar{m}_{\Omega_+}^2 = \bar{m}_\zeta^2 = (1500 \text{ GeV})^2$ $\bar{m}_\eta^2 = (2000 \text{ GeV})^2$					
$B_\Phi = B_\Omega = A_\zeta = A_\eta = A_{\Omega^+} = A_{\Omega^-} = m_{\zeta\eta}^2 = 0$ $B_\zeta^2 = (1400 \text{ GeV})^2$ $B_\eta^2 = (700 \text{ GeV})^2$					
RH neutrino and RH sneutrino sector					
$m_{\nu_R} = 63 \text{ GeV}$ $m_{\bar{\nu}_R} = 65 \text{ GeV}$ $\kappa = 0.9$					
$y_N = (3.28i, 6.70i, 1.72i) \times 10^{-6}$ $h_N = (0, 0.227, 0.0204)$					
Other SUSY SM parameters					
$m_{\tilde{W}} = 500 \text{ GeV}$ $m_{\tilde{q}} = m_{\tilde{l}} = 5 \text{ TeV}$					
(ii) Predictions of the Benchmark points					
Non-decoupling effects					
$\varphi_c/T_c = 1.3$ $\lambda_{hhh}/\lambda_{hhh} _{\text{SM}} = 1.2$ $B(h \rightarrow \gamma\gamma)/B(h \rightarrow \gamma\gamma) _{\text{SM}} = 0.78$					
Neutrino masses and the mixing angles					
$(m_1, m_2, m_3) = (0, 0.0084 \text{ eV}, 0.0050 \text{ eV})$ $\sin^2 \theta_{12} = 0.32$ $\sin^2 \theta_{23} = 0.50$ $ \sin \theta_{13} = 0.14$					
LFV processes					
$B(\mu \rightarrow e\gamma) = 3.6 \times 10^{-13}$ $B(\mu \rightarrow eee) = 5.6 \times 10^{-16}$					
Relic abundance of the DM					
$\Omega_{\nu_R} h^2 = 0.055$ $\Omega_{\bar{\nu}_R} h^2 = 0.065$ $\Omega_{\text{DM}} h^2 = \Omega_{\nu_R} h^2 + \Omega_{\bar{\nu}_R} h^2 = 0.12$					
Spin-independent DM-proton scattering cross sections					
$\sigma_{\nu_R}^{\text{SI}} = 3.1 \times 10^{-46} \text{ cm}^2$ $\sigma_{\bar{\nu}_R}^{\text{SI}} = 7.7 \times 10^{-47} \text{ cm}^2$ $\sigma_{\text{DM}}^{\text{SI}} = 1.1 \times 10^{-46} \text{ cm}^2$					

In Fig. 2, we show the mass spectrum of the relevant particles in the benchmark scenario given in Table II. In this scenario, the Z_2 -even sector is similar to the nMSSM which can be distinguished from the MSSM by the spectrum of extra Higgs bosons. For example, the mass splitting between the charged Higgs boson and the heavy Higgs bosons is caused by the large mixing between doublet fields and a singlet field, which is necessary in order to reproduce the relic abundance of the DM.

In the benchmark scenario, φ_c/T_c is enhanced by the loop effect of Φ_u and Ω_- , which can also significantly affect the $h\text{-}\gamma\text{-}\gamma$ coupling and the triple Higgs boson coupling as shown in Table III. By precise measurement at future collider experiment such as ILC[8] of such the Higgs boson couplings, our benchmark scenario can be

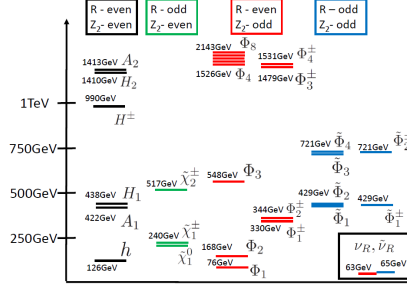


FIG. 2: The mass spectrum of the relevant particles in the bench mark scenario. The figure is taken from Ref.[2].

TABLE III: The deviations in the coupling constants from the SM values in the benchmark scenario.

Couplings	hWW	hZZ	$h\bar{u}u$	$h\bar{d}d$	$h\bar{\ell}\ell$	$h\gamma\gamma$	hhh
$\kappa_{h\phi\phi} = g_{h\phi\phi}/g_{h\phi\phi}^{\text{SM}}$	0.990	0.990	0.990	0.978	0.978	0.88	1.2

distinguished from nMSSM. In addition, the direct search of inert doublet particles[9] and inert charged singlet searches[10] at ILC can also provide a strong hint on the Z_2 -odd sector of the scenario.

IV. SUMMARY

We have attempted to propose a simple model to explain the three problems such as baryogenesis, tiny neutrino mass, and DM in its low energy effective theory and we have succeeded to find such a model based on SUSY $SU(2)_H$ gauge theory with confinement. We have introduced a benchmark scenario and we have discussed how to test it at future collider experiments.

Acknowledgments

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